

FIELD EFFECTS OF BUOYANCY ON LEAN PREMIXED TURBULENT FLAMES

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INTRODUCTION

The study of field effects of buoyancy on premixed turbulent flames is directed towards the advancement of turbulent combustion theory and the development of cleaner combustion technologies. Turbulent combustion is considered the most important unsolved problem in combustion science and laboratory studies of turbulence flame processes are vital to theoretical development. Although buoyancy is dominant in laboratory flames, most combustion models are not yet capable to consider buoyancy effects. This inconsistency has impeded the validation of theories and numerical simulations with experiments. Conversely, the understanding of buoyancy effects is far too limited to help develop buoyant flame models.

Our research is also relevant to combustion technology because lean premixed combustion is a proven method to reduce the formation of oxides of nitrogen (NO_x). In industrial lean premixed combustion systems, their operating conditions make them susceptible to buoyancy thus affecting heat distribution, emissions, stability, flashback and blowoff. But little knowledge is available to guide combustion engineers as to how to avoid or overcome these problems.

Our hypothesis is that through its influence on the mean pressure field, buoyancy has direct and indirect effects on local flame/turbulence interactions. Although buoyancy acts on the hot products in the farfield the effect is also felt in the nearfield region upstream of the flame. These changes also influence the generation and dissipation of turbulent kinetic energy inside the flame brush and throughout the flowfield. Moreover, the plume of an open flame is unstable [1] and the periodic fluctuations make additional contributions to flame front dynamics in the farfield. Therefore, processes such as flame wrinkling, flow acceleration due to heat release and flame-generated vorticity are all affected. Other global flame properties (e.g. flame stabilization limits and flame speed) may all be coupled to buoyancy. This problem poses major challenges to combustion modeling due to its need for a computation domain extending into the farfield and full specifications of upstream, wall and downstream boundary conditions.

OBJECTIVE

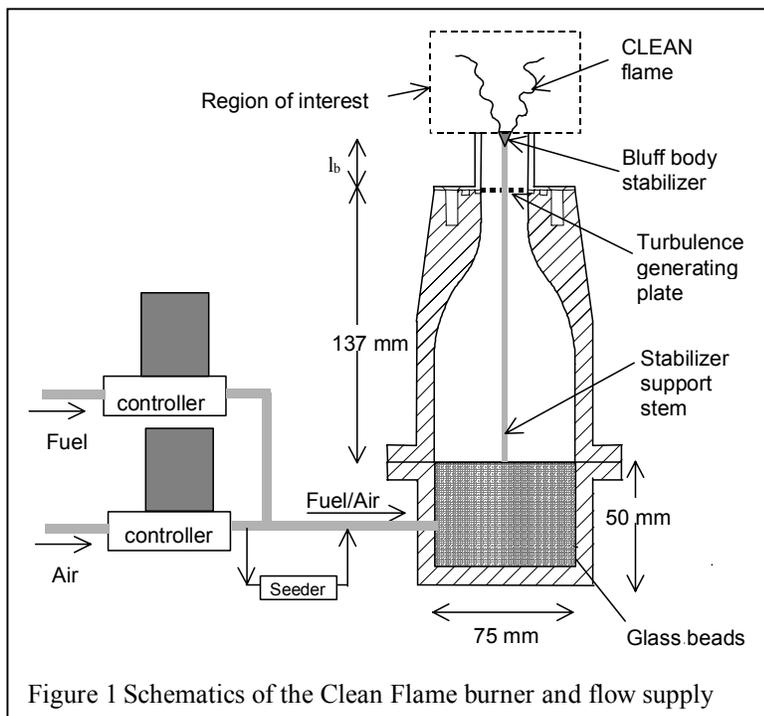
The overall objective of our flight experiments planned for the Combustion Integrated Rack (CIR) onboard the International Space Station is to quantify the global flowfield and local flame/turbulence interactions of μg flames. Buoyancy is omnipresence in terrestrial experiments. Removing buoyancy through prolonged reduced gravity is the only means to obtain statistically stable and accurate benchmark μg data to characterize complex flame/turbulence interactions. Buoyancy contributions to these processes will be elucidated by comparing with extensive terrestrial studies flames subjected to normal (+1g) and reversed (-1g) gravity. The flight experiments will be focussed on determining the effect of buoyancy on three aspects of turbulent flames: (1) the mean

characteristics of the scalar and velocity fields; (2) local turbulence/flame coupling processes, determined by the conditioned velocity statistics and expressed in terms of the reaction rate and turbulent transport; and (3) combined effects of buoyancy and thermal/diffusive instabilities.

EXPERIMENTAL CONFIGURATION, DIAGNOSTICS & ANALYSIS

The experimental configuration selected for the flight experiments is an axi-symmetric Cone-stabilized LEAN (CLEAN) flame. (Figure 1). This flowfield is amenable to numerical modeling and theoretical analysis. In many respects, this flowfield is similar to that generated by rod-stabilized V-flame [2] but without the influences of flame edge effects. The burner has an exit diameter of 17 mm with a turbulence generating plate placed at about 20 mm upstream of the exit. The bluff body stabilizer is cone shaped and supported by a stem anchored at the burner's central axis.

The same methodology, data acquisition and data analysis methods we have developed for laboratory flames will be used ultimately for the flight experiments. The emphasis is to obtain statistically stable sets of detailed velocity and scalar data for the analysis of conditional statistics and turbulence transport processes. We plan to measure the scalar field by a Planar Imaging of Flame Fronts (PIFF) method (i.e., planar laser induced fluorescence of OH [2] or Mie scattering from oil aerosol). Particle image velocimetry (PIV) is the preferred method to measure mean and RMS velocities. The data will be analyzed to obtain mean properties as well as detailed flame structures and turbulence transports.



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GROUND-BASED LABORATORY

EXPERIMENTS

In preparation for the flight experiments, we have conducted a series of laboratory investigations to determine that the CIR system and its support fulfill all the scientific requirements of the experiments. These studies have helped to determine the appropriate sizes of the burner and the stabilizer, and to optimize the design of the ignition and exhaust systems.

We have also developed a Particle Imaging Velocimetry (PIV) system to investigate the flowfields of CLEAN flames subjected to +1g and -1g. The system consists of a New Wave Solo PIV laser which produces double 120 mJ pulses at 532 nm and a Kodak Megaplex ES 4.0 digital frame-straddling camera with 2048 by 2048 pixel resolution. The optics were arranged to capture a 6 by 6 cm field of view (30.27 μm per pixel resolution). The flow was seeded with 0.3 μm Al_2O_3

particles. Data acquisition (PIVACQ) and analysis (PIVPROG) were performed using software developed by one of the authors (MPW).

Twelve sets of PIV data have been obtained thus far. They consist of three laminar and three turbulent CH₄/air flames with equivalence ratios, $\phi = 0.7, 0.8$ and 0.9 in $+1g$ and $-1g$. The mean flow velocity U for all the experiments were 3 m/s. For the turbulent flames, turbulence produced by the grid is slightly anisotropic with $u' = 0.44$ m/s and $v' = 0.3$ m/s.

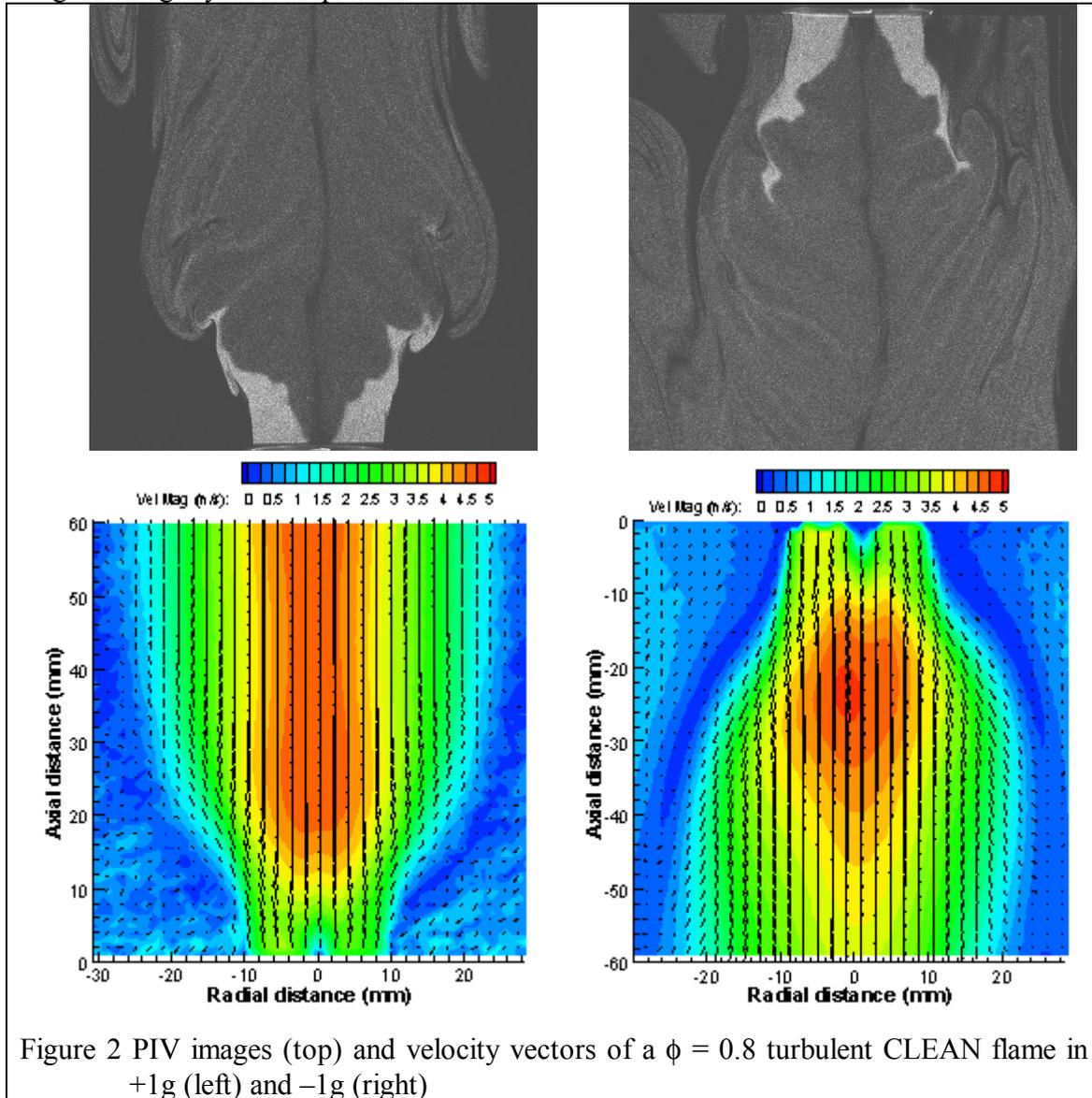


Figure 2 PIV images (top) and velocity vectors of a $\phi = 0.8$ turbulent CLEAN flame in $+1g$ (left) and $-1g$ (right)

Figure 2 compares the raw image and velocity vectors measured in a $\phi = 0.8$ turbulent flames subjected to $+1g$ and $-1g$. Also shown in the background are contours of the velocity magnitude $|U| = (U^2 + V^2)^{1/2}$. Due to high contrast between the Mie scattering intensities in the reactants and the products regions, the wrinkled flame fronts are clearly discernable on the raw images. Therefore, PIV may be the only diagnostics needed for the flight experiments because the essential scalar information can be deduced from the analysis of the flame wrinkle geometry. The velocity contours also shows that in $+1g$, buoyancy forces coupled with flame generated flow

acceleration help to maintain a high velocity region along the centerline. In contrast, buoyancy forces acting against the heat release effects cause the flow to decelerate in $-1g$.

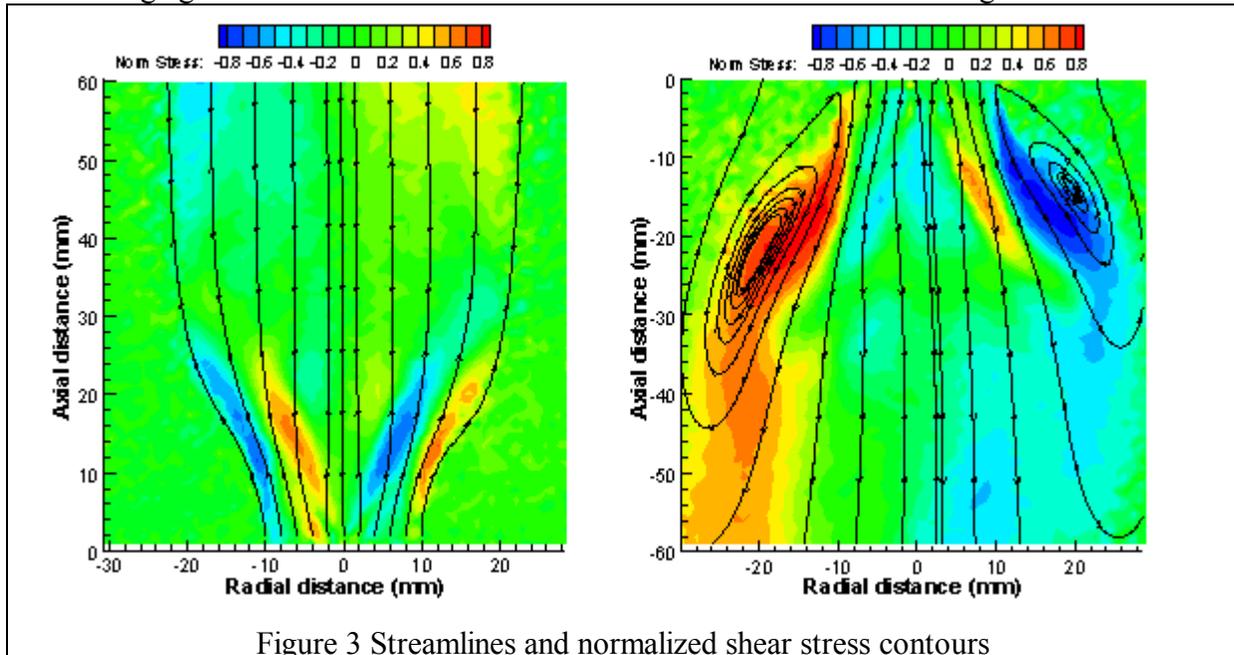


Figure 3 Streamlines and normalized shear stress contours

Other differences between the flowfields of $+1g$ and $-1g$ flames are shown in Figure 3. In $-1g$, the streamlines clearly trace regions of strong flow recirculation outside the flame, and the farfield region has a divergent trend. The normalized shear stress contours in the background show that the recirculation zones of the $-1g$ flame are marked by high shear regions that are substantially broader than those found in the $+1g$ flame. The two smaller shear regions closer to the centerline of both $+1g$ and $-1g$ flames are generated by the wrinkled flames. Though this shear stress is artificial due to intermittent contributions from the velocities in the reactants and the products [3], differences in the stress levels in the $+1g$ and $-1g$ flames are indicators of changes in the flame generated flow dynamics. Further analysis of the PIV data to obtained conditioned velocities will help to quantify these changes to give better insights.

PLANNED PARABOLIC FLIGHT EXPERIMENTS

To continue with the development of the flight experiments, we plan to conduct PIV measurements on board parabolic flights. The experience will guide the development of a PIV system for CIR and to address issues concerning chamber venting and seeding requirements. Though the duration of the parabola are not sufficient to allow the CLEAN flames to reach steady state the PIV data provide preliminary results on the flowfield of μg CLEAN flames.

REFERENCE

- [1] Kostiuk, L.W. and Cheng, R.K., *Combustion and Flame* 103:27 (1995).
- [2] Cheng, R.K. and Bedat, B., *Combustion and Flame* 116:360 (1999).
- [3] Cheng, R.K., *Combustion Science and Technology* 41:109 (1984).